AFRL-DE-PS-TR-2004-1102

AFRL-DE-PS
TR-2004-1102

LITE Experimental Support II

David J. Gallant

Boeing LTS, Inc.
PO Box 5670
Albuquerque, NM 87185

July 2004

Final Report

AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

STINFO COPY

This report has been approved for publication.

//signed//
RICHARD W. BERDINE
Project Manager

//signed//
LE ANN D. BRASURE, Lt. Col., USAF
Chief, High Power Solid-State Laser Branch

//signed//
L. BRUCE SIMPSON, SES
Director, Directed Energy Directorate

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 01-07-2004	**2. REPORT TYPE** Final Report
3. DATES COVERED *(From - To)*	01-Aug-2000 — 30-Jun-2004
4. TITLE AND SUBTITLE	LITE Experimental Support II
5a. CONTRACT NUMBER	F29601-00-D-0169 (TO 0007)
5b. GRANT NUMBER	
5c. PROGRAM ELEMENT NUMBER	62605F
6. AUTHOR(S)	David J. Gallant
5d. PROJECT NUMBER	4866
5e. TASK NUMBER	LR
5f. WORK UNIT NUMBER	AD
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	Boeing LTS, Inc. PO Box 5670 Albuquerque, NM 87185
8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)	AFRL/DELO 3550 Aberdeen Ave SE Kirtland AFB NM 87117-5776
10. SPONSOR/MONITOR'S ACRONYM(S)	
11. SPONSOR/MONITOR'S REPORT NUMBER(S)	AFRL-DE-PS-TR-2004-1102
12. DISTRIBUTION / AVAILABILITY STATEMENT	Approved for Public Release; Distribution is Unlimited.
13. SUPPLEMENTARY NOTES	

14. ABSTRACT

This report summarizes the technical activity provided under task order 0007 of the SLIDERS contract. This task provided for continued research and development, and on-going operations support for the LITE fiber laser development program.

15. SUBJECT TERMS
Lasers, Fiber, Semiconductor pump

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
Unclassified	Unclassified	Unclassified	Unlimited	18	RICHARD W. BERDINE
					19b. TELEPHONE NUMBER *(include area code)* (505) 853-0474

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

TABLE OF CONTENTS

1.0 INTRODUCTION

The SLIDERS contract encompassed several research efforts within the Semiconductor Laser Branch and the Solid State Laser Branch of the Laser Division, Directed Energy Directorate of the Air Force Research Laboratory. The scope of this contract included development, design, fabrication, procurement, management, operations and maintenance of optical, electronic, and mechanical systems, subsystems, and components. Principal efforts included theory and concept development, design analysis, laboratory operations, and semiconductor laser and diode-pumped laser development, operation and maintenance. Efforts also included the development, procurement, and operation of instrumentation to evaluate and characterize laser systems.

The objective of task 0007 under the SLIDERS contract was to provide continued support for research and development work on diode pumped fiber lasers. Efforts included support of fiber SBS and phasing experiments, set up and characterization of high brightness diode pumps systems, engineering, design and fabrication of custom experimental components, and laboratory operation and maintenance support. These efforts supported the DELO branch LITE program of the Directed Energy Directorate at the Air Force Research Laboratory.

2.0 TECHNICAL ACTIVITIES

2.1 STIMULATED BRILLOUIN SCATTERING EXPERIMENT

Stimulated Brillouin Scattering (SBS) is a parasitic nonlinear process set up in a dielectric medium (glass fiber) under the influence of coherent radiation. A sufficiently intense coherent wave propagating in the forward direction will set up a periodic index grating in the glass fiber due to electrostriction. Subsequent radiation traveling in the same direction will be back scattered due to the imposed index grating. The net effect is to rob forward propagating power and send it in the reverse direction. The factors that affect the “threshold” for SBS initiation include the light wave intensity, the coherence and bandwidth of the light, interaction length, thermal effects, and the properties of the glass. Single mode fiber lasers can be particularly susceptible to SBS due to the high intensity of the light in the fiber core.

To mitigate the effects of SBS several approaches are possible. The first is to lower the intensity of the light by using “large area core” fibers, where the lowest order mode is propagated in a carefully prepared larger core while the higher order modes continue to be suppressed. This device would continue to operate as a single mode device, and have the added benefit of having a lower power density at the fiber end facet. This approach requires access to large area core fibers which are only recently commercially available, or the ability to draw custom fibers. The second approach is to reduce the light coherence thereby “washing out” the imposed gratings. Boeing investigated this approach using the technique of phase modulation.

By imposing a periodic phase modulation (sin wave) on an optical signal using an optical phase modulator, it is well known that optical frequency side bands are generated. The intensity and number of side bands is a function of the intensity of the phase modulating signal (depth of modulation), and the sideband frequency separation is a function of the modulation frequency. This technique has been investigated by others for its potential in the communications arena however there is limited information on the degree of SBS suppression using this technique.

We set up an experiment to measure SBS thresholds using two kilometers of commercially available passive, single mode fiber, a narrow linewidth Nd:YAG laser, and a commercial phase modulator driven by an RF generator and power amplifier. Optical components and hardware were located and an experiment beam train was developed. Measurements of the injection laser beam parameters were completed using a Mode Master instrument. Optimum lensing was calculated to allow the beam to get through the phase modulator properly. A Super Cavity spectrum analyzer was set up and the laser spectrum was observed. The phase modulator driver and the RF frequency generator were also set up and the performance of the phase modulator was verified. Coupling optics for beam alignment into the test fiber were set up. Different microscope objectives were used and the power through the fiber was measured. A 20x objective was found to be the best. While this objective has a larger numerical aperture than the fiber it produces a smaller spotsize which compensates. After accounting for transmission losses through the fiber, a fiber coupling ratio of 60 % was calculated into the single mode fiber. A second fiber was also measured and the fibers were fused together. Measurements on the (2 Km) fused fiber indicated very low fuse loss. During the course of the fiber alignment it was observed that the power at the input to the fiber was changing. The erratic behavior of the laboratory temperature coupled with the temperature sensitivity of the phase modulator was to blame. Efforts were made to align the modulator better to reduce the temperature sensitivity. A fast photodetector was set up and aligned to look at the backward propagating light to verify an SBS signature as opposed to light backscattered from the fiber entrance facet. Calibration of the spectral content versus phase modulator frequency and RF power level were completed.

The laser power launched into the fiber was varied and the return signal (SBS) was measured and plotted against the launched power. The threshold was defined as the launched power where the SBS signal started to increase and the power transmitter through the fiber started to be clamped.

Measurements of passive fiber SBS thresholds were obtained under various phase modulation conditions. The SBS threshold, with no phase modulation, was found to be 28 mW of launched laser power under our test conditions. This corresponds to a 56 W-meter threshold. With phase modulation the SBS threshold increased, with the exact threshold depending on modulation depth and frequency. In general, the greater the modulation frequency (50 MHz-200MHz) the greater the threshold, and the greater the modulation depth the greater the threshold. This is consistent with current theories where SBS thresholds are sensitive to the excitation bandwidth. Under certain test conditions the thresholds increased by factors of 2-3. As higher frequencies and modulation depths were studied we encountered experimental difficulties such as heating up of the phase modulator under conditions of high frequency (> 150 MHz) and high driving power (> 120 W), and harmonics that were produced by the RF generator. Efforts were made to overcome these limitations but the effects made the experiment more difficult to quantify.

The results of the experimental work, i.e. the SBS threshold as a function of phase modulation frequency and depth of modulation were summarized in graphical format and a description of the experiment and its results were presented at the 2002 SS DLTR conference in a paper “Reduction of Stimulated Brillouin Scattering in High Power Fiber Lasers.”

2.2 DIODE ARRAY LIFETIME EXPERIMENT

Semiconductor laser arrays (stacked arrays), used for high power fiber laser and solid-state laser pumping, have been increasing in power and brightness over the years. However the critical issues of reliability, long-term performance and lifetime of these high power arrays are not fully understood or resolved. Commercial operation of semiconductor laser arrays has resulted in greater degradation rates than the reported lifetime data. The issues of lifetime and failure mechanisms of high performance 40-60 Watt/bar CW arrays are particularly important due to the more complex packaging issues, higher heat loads, and the fact that open failures of any bar leads to failure of the array (for series operation). The real world performance of arrays and cooler technology needs to be addressed and quantified.

In response to this need Boeing personnel assembled a reliability experiment to assess diode array lifetime issues. Space for the experiment was identified and modifications which were required for power and cooling were completed. Our computer controlled experiment operated CW or pulsed, both of which could be cycled on and off for long term thermal stressing, which has been shown to lead to higher degradation rates. The pulsed mode format could be operated with pulses from 40 microseconds to 500 microseconds, at up to 50% duty cycle.

The design of the experiment called for monitoring array output power periodically over the course of its operation and capturing thermal and nearfield images to study whether precursors to failure could be identified. A beam train incorporating a motorized rail for the power meter, and reimaging optics and filters for the thermal and near IR cameras was engineered to allow computer control of all data gathering.

A high current array driver control board was engineered by Boeing and fabricated on a water cooled mounting plate. The board was built to modulate the array current and to turn it on and off. High current electronic diodes were set up as a dummy test load and testing up to 30 amps was successful.

To allow computer control of the experiment, Boeing personnel developed a computer control system using a commercially available computer and incorporating numerous safety features such as coolant sensors for temperature, pressure, and flow, and a computer watchdog circuit to turn the system off in the event the control computer locked up. We designed and built custom control software using LabVIEW which monitored the safety features, took data, and controlled instrumentation. The software was built to operate the experiment 24 hours a day and automatically gather the required data.

Requirements for cooling of the high power array and the power meter were outlined and Boeing personnel set up two cooling systems, one for each component. The array coolant system incorporated a commercial water chiller, particulate filters, a UV sterilizing unit, a deionization tank, a pressure tank for limited emergency use in the event the pump failed, and instrumentation for monitoring the water pressure, temperature, flow, and resistivity. Flow switches were used on both the array and power meter systems to automatically turn off the array if loss of coolant was detected.

An experiment cover was designed and fabricated. This cover, which acted primarily as a safety device to allow unattended operation of the device by providing shielding from the laser scatter, also allowed access to the experiment components, and allowed for providing a filtered air stream and dust control. The enclosure doors were outfitted with microswitches to turn the array off in the event the door was opened.

A Nuvonyx 1KW, 800 nm wavelength multibar array incorporating a copper "micro-channel" cooler was obtained for initial testing. The testing of the array began with an initial microscope examination and documentation of the bars. Unusual output facet characteristics were noted and the solder joint was inspected to locate potential problems such as excess solder near the active region or excess bar overhang, which may result in increased front facet temperatures. The array was set up and connected to the coolant system. Proper operation was verified and initial L/I measurements and the spectrum were recorded for comparison purposes and to ensure the array was working within specifications.

The array was lifetest operated CW at its rated electrical current in a cyclical format of 10 minutes on and one minute off to increase the thermal stress on the array. The laser optical power was measured directly during each on cycle and recorded by the computer. At every third cycle the power meter was moved aside under computer control, and a video frame was automatically recorded of the near field at low current to access the state of each bar/emitter and identify failures, and a thermal image was taken at a higher current level to identify hot spots, or regions that were increasing in temperature possibly caused by facet absorption or solder voids.

The primary mechanism we used to access the health of the array was the output optical power. At the start of the testing the current to the array was set to the manufacturers' recommended operating point (55 Amps) and the device output was approximately 800 watts. The initial power measurements, for time less than 400 hours, show a somewhat unstable behavior. This initial instability appears to be due to the coolant water flow conditions. In this region of time the flow was set higher than the recommended setting resulting in higher coolant pressure. It appears that the increased coolant pressure may have bowed the array bars resulting in erratic power output. Once the coolant flow was set to the recommended value (2 gpm), the power increased slightly and became stable with negligible degradation during the period from 400 to 1000 hours.

At the 1000 hour mark the array output power was very stable, and there were no indications of an early failure. At this point in time it was decided to increase the array operating current in order to accelerate the degradation of the device, to be able to ascertain failure mechanisms more quickly. The current was stair cased up to 70 Amps and held constant. Over the next 1500 hours the power dropped from 1050 watts to 1015 watts which is a degradation rate of 2.2% per thousand-hours. At this rate the power would have dropped to 820 watts after a total of 10,000 hours. However at approximately 2600 hours of run time the array suffered catastrophic damage and the power dropped off quickly.

The sudden nature of the array failure, the visibly extensive damage to the bars, and evidence of melted and evaporated indium strongly suggest that the array coolant was compromised. The coolant flow rate and the coolant inlet pressure were measured as a function of array on-time. The initial coolant flow rate was set slightly higher than the recommended setting (2.4 gpm vs 2 gpm recommended) which resulted in a high inlet pressure. The flow rate was subsequently adjusted to the nominal correct setting (2gpm) at the 400 hour point with the inlet pressure set to 40 psi. We attempted to keep both the flow rate and the pressure at their correct setting, however the long term trend was for the flow to decrease and the inlet pressure to increase. This behavior is consistent with a restriction forming in the heat sink channels, probably due to corrosion of the copper heat sink. At approximately 2400 hours there is a sharp increase in inlet pressure required to get the correct flow, signaling further blockage due to a small particle in the coolant or some corrosion breaking free and getting trapped in a channel which has been narrowed by corrosion. We continued our attempt to maintain coolant flow without driving the pressure too high. At 2600 hours there is another increase in pressure and the flow continues to diminish. Shortly after resetting the flow, one of the bars of the array overheated and failed. Subsequently more bars failed and the power output dropped sharply.

The device was removed from the test stand and characterized under a low power microscope. It was subsequently sent to the Materials and Manufacturing Directorate at Wright Patterson Air Force Base for disassembly and further electron microscope analysis. The results of these tests showed evidence of copper oxide contamination in the coolant channels and also the presence of copper oxide on the diode facets where presumably corrosion under the diode bars allowed coolant to escape carrying copper oxide with it.

Other activity along these experimental lines involved setting up a second lab area to support additional array lifetime testing. Modifications to the new lab area were completed and equipment was ordered. The test plan was modified and a new test stand was engineered. A new coolant system was designed based on our previous experience, to allow the simultaneous cooling of four arrays. Extensive work was done on plumbing the new coolant system, and buildup of the new lab area is on-going.

2.3 OTHER SUPPORT ACTIVITY

As part of the fiber laser development support effort a number of experimental components were designed and fabricated by Boeing. A water cooled fiber spool package was fabricated, assembled and leak tested. Water fittings were ordered and installed, and the spool was made ready for optical testing. A fiber winding apparatus was also designed and built to allow for easy winding of fiber onto the cooled spool. This spool allowed for fiber laser gain measurement to be made as a function of laser temperature.

Boeing also completed mechanical design work on parts for a breadboard fiber isolator experiment including magnet holders, magnet covers, two adapter plates, and fiber posts. This setup was designed to explore the possibility that an all fiber (no bulk optics) optical isolator could be realized. Initial experiments showed that more control was required so Boeing engineered an upgrade to the fiber isolator experiment that enabled the magnet holders to revolve and be locked around the optical fiber coils allowing tuning of the induced birefringence.

Boeing also completed design work on a fiber coupling station including V-block fiber guides, fixture alignment bocks, and modified clamp tips. Related to this work was the procurement of glass channel and microtubing for fiber splice packaging.

A stackable water cooled heatsink platform was designed and fabricated. This design allows for three laser assemblies to be stacked, yet be electrically and thermally isolated from one another.

Design and fabrication of an experimental fixture for beam combining was also completed. This assembly consisted of a pentagonal rail system that carried a series of mirror assemblies. Adapters for Newport tip/tilt mounts were integrated into the system. An alignment fixture for precise spacing and gluing was also designed and fabricated for this experiment. Testing of this alignment tool was completed with the use of microscope slides as dummy optics.

Heat sinks were designed for both prototype and commercial laser packages, and anodized aluminum beam shields were fabricated. A fixture for the Fiber Processing shop was designed, fabricated and anodized. This fixture will adapt existing hardware to allow multiple fiber ends to be microscopically examined. A new fiber clamp was also designed and fabricated. The “vee block” clamp facilitates fiber handling and limits induced stress in the fiber when clamped.

Boeing personnel also completed an electro-optical controller chassis layout for a fiber phasing/beam combining experiment intended to study fiber optic phasing properties. A circuit board was fabricated and wired for electronic control of the E.O. phase modulator, Mini-circuit RF components were mounted on the chassis, and modifications were made to mount new circuit components as needed.

Six high power fiber optic coupled lasers from Laser Line were ordered and installed to support the optical pumping of new fiber laser designs. This required hiring and coordinating of subcontractors to modify the laboratory electrical service, and to install the needed plumbing and chillers. Lab floor tiles were custom cut for plumbing and control lines. In addition, modifications to the HX2000 chiller were completed including check valves, new pressure gauges and quick release hardware for the system. The Laser Line power supplies were positioned and fitted with quick/connect hardware and cooling lines. New plumbing was run for the remotely positioned twin head delivery system. New Laser Line head heat sinks were designed and fabricated. The modified design allowed for both styles of Laser Line head packages to be mounted and centered on the table hole pattern, facilitating beam train layout.

3.0 CONCLUSIONS

The ability to raise the threshold for SBS has important consequences in the development of fiber lasers. The technique we have investigated, which relies on phase modulation of the injected laser light, is straightforward and provides flexible operating conditions. Our results showed that under all phase modulation conditions measured, the SBS threshold was greater than that for no modulation, the limit being the bandwidth of the experimental equipment. Future work of interest would involve applying this technique to active (doped) fibers and measuring the SBS threshold variation. The amount of SBS reduction required in an operational fiber laser system is also not known at this time. A theoretical investigation could be undertaken to explore this issue.

The study of diode array reliability is important to develop robust fiber and solid state laser pump systems. It is evident from our initial reliability results that corrosion within the copper microchannel cooler is a problem. The corrosion led to pinhole formation in the stripe regions of the cooler and eventually to melting of the indium solder where the cooler was most compromised. Corrosion is a complex phenomenon which can be influenced by a number of factors including the materials, cooling fluid properties, surface roughness of the channels, heat, and stray electrical currents. A copper microchannel cooler is susceptible to chemical corrosion if the pH is not optimum, if the coolant absorbs free oxygen, or galvanic corrosion may be present if other metals such as aluminum, zinc, and iron are present in the coolant system. Newer cooler systems are more fully plated internally with gold which should help reduce the corrosion problem. Careful attention to the properties of the coolant fluid is also required to ensure long array lifetime. Reliability studies should continue to assess newer cooling systems, brighter arrays, and improved manufacturing techniques.

4.0 PAPERS AND PRESENTATIONS

"Reduction of Stimulated Brillouin Scattering in High Power Fiber Lasers**",** Gallant D; Stohs J; Benham V, *Conference: 2002 Solid State and Diode Laser Technology Review (SSDLTR), Albuquerque NM*

"Diode Array Reliability Experiment (DARE)**",** Gallant D; Boeckl J, *Conference: 2002 Fifth Annual Directed Energy Symposium, Monterey CA*

"High Power Diode Array Reliability Experiment**",** Gallant D; Boeckl J, *Conference: 2003 SPIE Photonics West, San Jose CA*

"Diode Array Reliability Experiment**",** Gallant D, *Conference: 2003 Solid State and Diode Laser Technology Review (SSDLTR), Albuquerque NM*

"Diode Array Reliability Experiment (DARE)**",** Gallant D, *Conference: 2004 SPIE Photonics West, San Jose CA*

"High Power Diode Array Failure Analysis**",** Gallant D; Boeckl J, *Conference: 2004 Solid State and Diode Laser Technology Review (SSDLTR), Albuquerque NM*

DISTRIBUTION LIST

DTIC/OCP 8725 John J. Kingman Rd, Suite 0944 Ft Belvoir, VA 22060-6218	1 cy
AFRL/VSIL Kirtland AFB, NM 87117-5776	1 cy
AFRL/VSIH Kirtland AFB, NM 87117-5776	1 cy
Official Record Copy AFRL/DELO/Rick Berdine	3 cys